Alternative High-Performance Motors with Non-Rare Earth Materials

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DOE Peer Review Presentation

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Overview

Timeline

- Start: October 1, 2011 (official kickoff with DoE February 7, 2012)
- End: January 30, 2016
- 78% complete (Kickoff meeting Feb. 7, 2012)

Budget

- $ ~12M total budget
- $ ~6M DOE share
- $ ~6M GE cost share

•Funding received from the DoE to date: $ 4,699,634

Barriers

Very challenging set of specs

- High efficiency over a wide speed and load ranges
- High power density and high coolant inlet temperature
- Low cost targets based on 100,000 units/year
- High speed poses mechanical challenges
- No rare-earth permanent magnets

Partners

- GE Global Research (lead)
- GE Power Conversion/GE Licensing
- University of Wisconsin-Madison
- North Carolina State University
- University of Akron
- ORNL
- NREL
- McCleer Power
- Ames National Lab
- Arnold Magnetics

The Problem

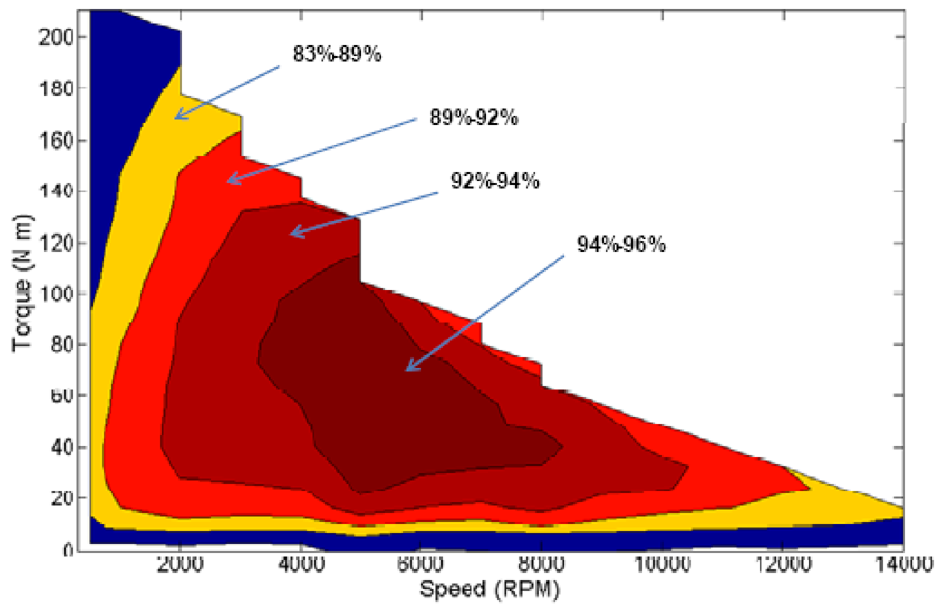
- The specifications for hybrid vehicle motors are challenging in terms of power density, efficiency and cost. This requires a comprehensive approach to advance the state of the art, including novel concepts to push past barriers.
- High speed is key to high power density
- High speed leads to higher electrical frequency
- Higher stator core and rotor losses
- On top of all these challenges, eliminating rare-earth permanent magnets makes the problem an order of magnitude more challenging

Project Objective (FY15/FY16)

Items	Specification
Max. Speed	14,000rpm
Peak Power	55kW @ 20% speed for 18sec
Maximum Current	400Arms
Cont. Power	30kW @ 20~100% speed @ Vdc=325
Efficiency	Refer to target efficiency map
Operating Voltage	200~450V (325V nominal)
Back EMF	<600Vpk line-to-line @ 100% speed
Torque Pulsation	<5% of Peak Torque @ any speed
Characteristic Current	< Maximum Current
Weight	≤35kg
Volume	≤9.7L
Cost @100k	≤$275
Ambient (outside housing) Operating Temperature	-40~140°C
Coolant inlet	105°C, <10LPM, 2psi drop, <20psi inlet
Minimum isolation impedance-phase terminal to GND	1Mohm

- Finish build and testing of the down-selected 4 motor prototypes
- Down-select and build/test final 55kWpk non-rare earth motor to meet DOE specifications

Figure 1. Motor Efficiency Targets



Relevance

Developing a low-cost, high-performance advanced traction motor is a key enabler to meeting the 2020 technical targets for the electric traction system. Elimination of rare-earth permanent magnets is very strategic in terms of eliminating the uncertainty regarding sustainability of rare-earth magnets

Table 1. Technical Targets for Electric Traction System

	2010[a]	2015[b]	2020[b]
Cost, $/kW	<19	<12	<8
Specific power, kW/kg	>1.06	>1.2	>1.4
Power density, kW/L	>2.6	>3.5	>4.0
Efficiency (10%-100% speed at 20% rated torque)	>90%	>93%	>94%

[a] Based on a coolant with a maximum temperature of 90°C.

[b] Based on air or a coolant with a maximum temperature of 105°C.

[c] A cost target for an on-board charger will be developed and is expected to be available in 2010.

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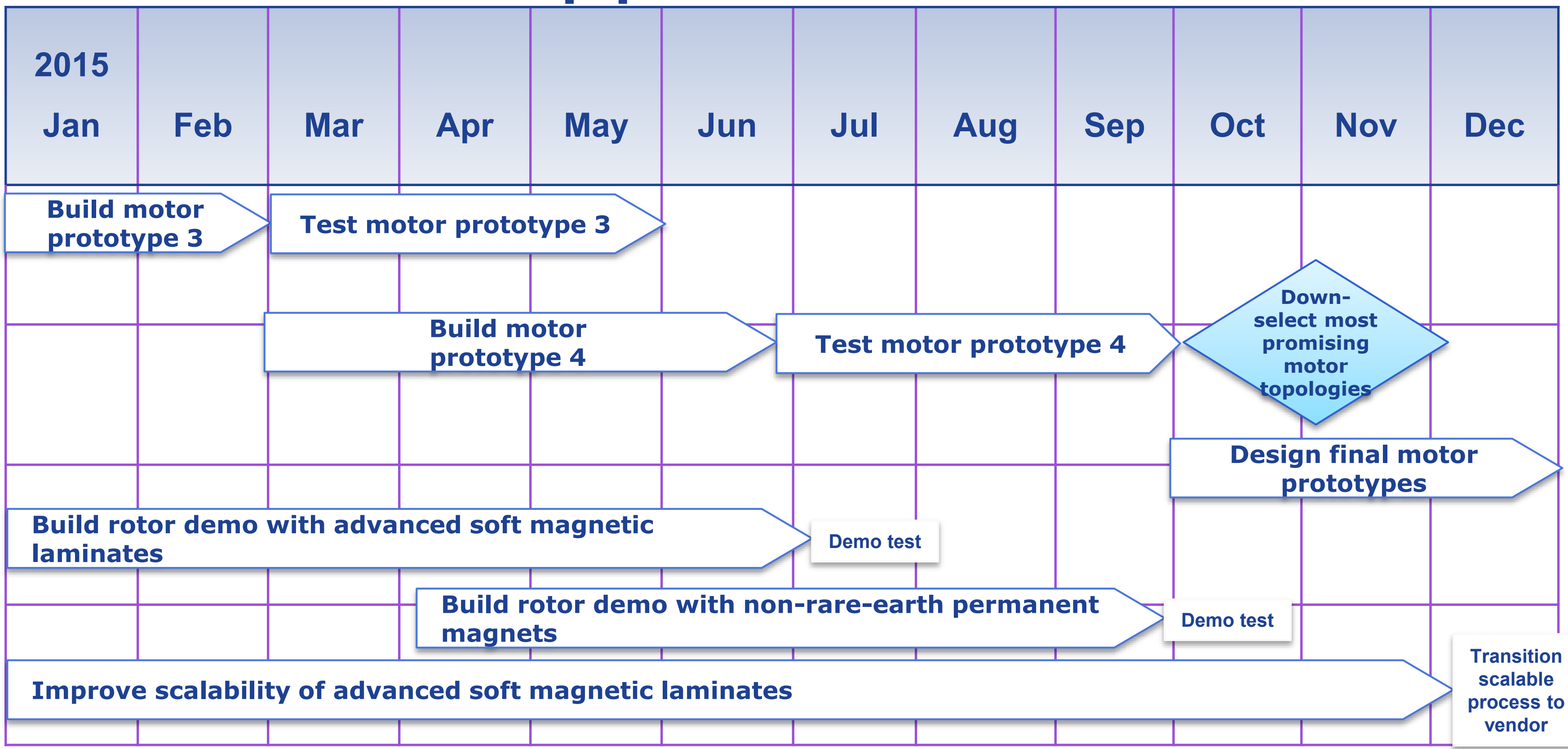
Project Uniqueness and Impacts

- The project proposes a very comprehensive approach in terms of identifying the technologies that will meet the required performance
- The project will explore various motor topologies; some include no magnets at all and some include non-rare earth magnets
- Some of the motor topologies use only conventional materials while others will be enabled by advanced materials that will be developed under the project
- Advanced materials including magnetic as well as electrical insulating materials will be developed to enable the motors to meet the required set of specifications
- Advanced motor controls and thermal management techniques will also be developed.
- By evaluating the wide range of motor topologies and advanced materials, down-selected topologies/materials are expected to meet the required set of specifications

Approach

- Perform tradeoff study of various motor topologies (≈10 topologies: some use conventional materials while others will be enabled by new materials)
- Identify promising scalable materials and produce coupons showing the expected properties (1 hard magnetic, 2 soft magnetic, 1 dielectric)
- Down-select promising topologies/materials
- Design/build/test 2-3 proof-of-principle motors
- Down-select final motor topology
- Design/build/test 3 identical motors as the key project deliverable(s)
- Develop cost model for the final motor

FY15/FY16 Approach and Milestones



Go No/Go Decision Point: The key go no/go decision point will be after the 4 down-selected motor prototypes are built and tested to determine based on test results how do they compare to the baseline IPM with rare-earth magnets

Challenges/Barriers: The set of specifications is very challenging and eliminating rare-earth permanent magnets is a big hit in terms of torque density and efficiency

Accomplishments to Date

Motor accomplishments:

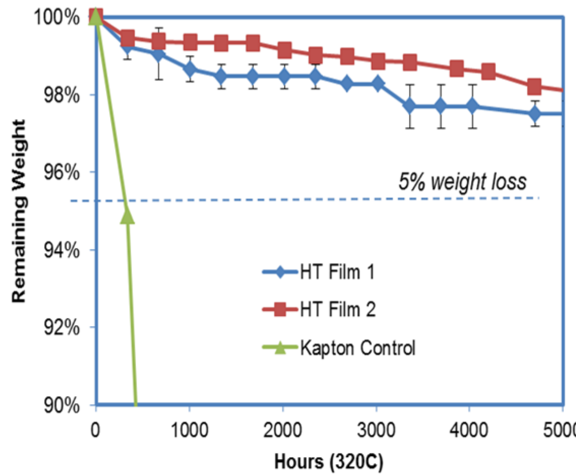
- Continue to evaluate more motor topologies (more than 10 evaluated so far)
- Down-selected the first 4 topologies :
  - First prototype has reduced rare-earth content (built and fully tested)
  - Second prototype has non-rare earth magnets (built and fully tested)
  - Third prototype has no magnets and includes one of the advanced materials (built and currently being tested)
  - Fourth prototype is a scaled-down version that includes the dual-phase magnetic material is currently being built

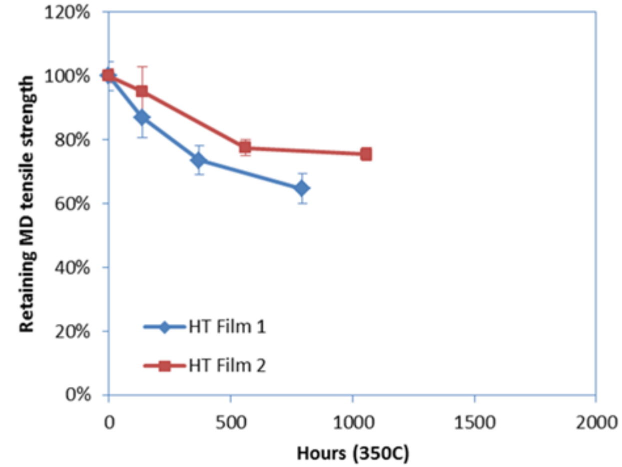
Materials accomplishments:

- Developed and scaled-up processing of high temperature (>250 °C) slot-liner insulation.
- Developed method for locally patterning non-magnetic regions on motor lams with < 100 µm interface widths that are stable > 5000 hours at 180 °C
- Produced test laminate with locally non-magnetic regions in preparation for scale-up.
- Demonstrated GE-synthesized non-rare-earth permanent magnets with Hci > 2.0 kOe. This technology was not selected for scale-up based on motor performance targets.
- Develop higher-strength silicon steel laminates. This technology was not selected for scale-up due to high core loss.

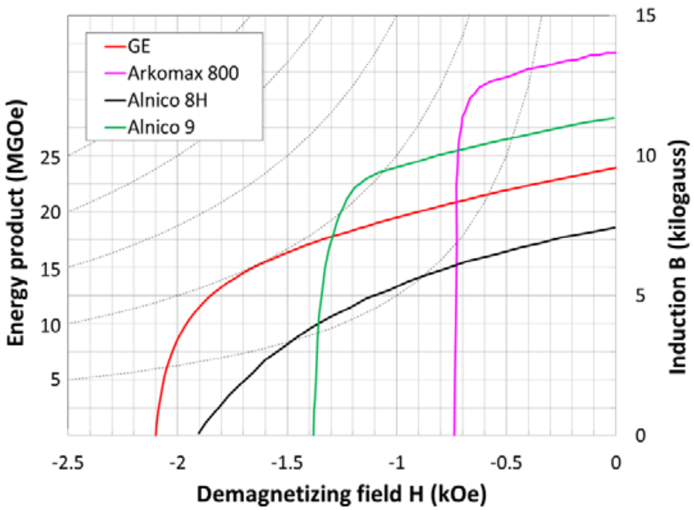
Materials accomplishments

Developed and scaled-up high temperature slot-liner insulation

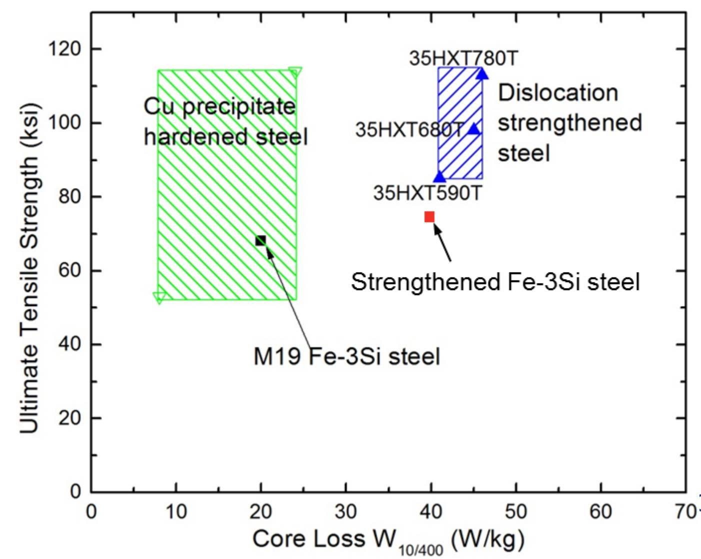




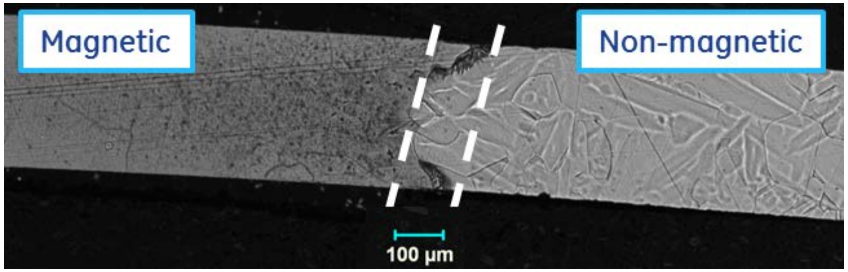
Enhanced coercivity in non-rare-earth



Higher-strength steel laminates

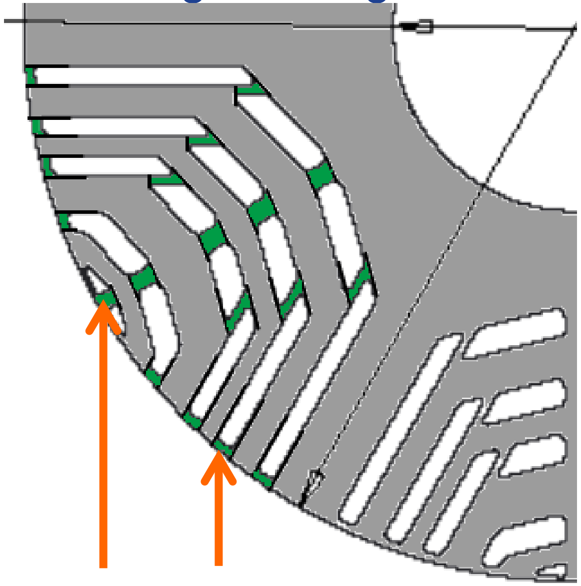


Materials accomplishments

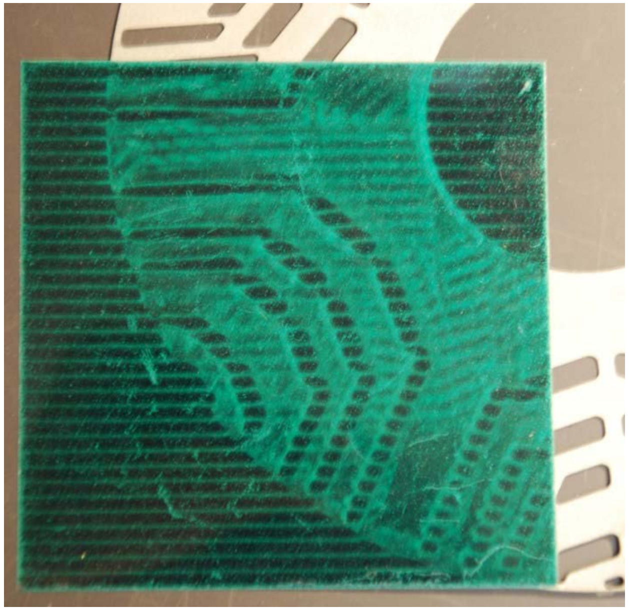


Cross section of interface between magnetic and non-magnetic regions

Alloy and process for producing motor laminates with locally patterned low µ regions for have been developed and are being scaled up for prototype demo

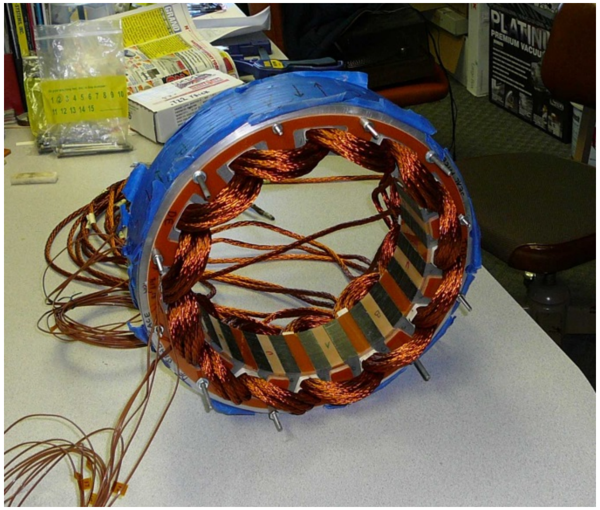


Non-magnetic bridges and posts patterned into magnetic laminate



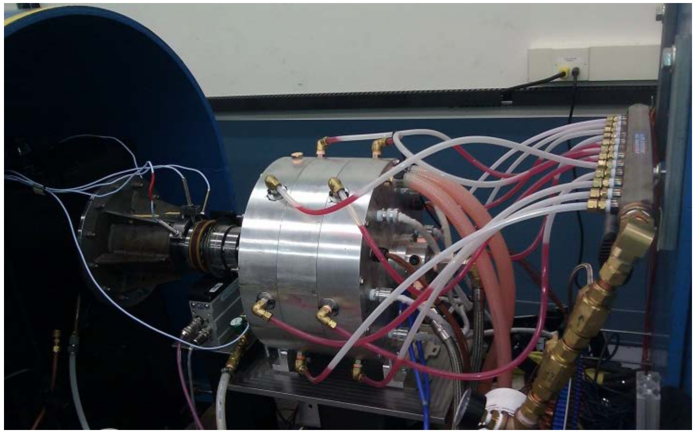
Stripe domain pattern shows through non-magnetic bridges and post

(1) Flux-Switching Dy-Free PM Motor Prototype

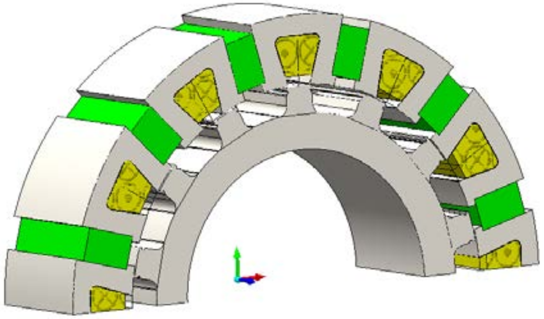


Stator

Rotor



Test Setup



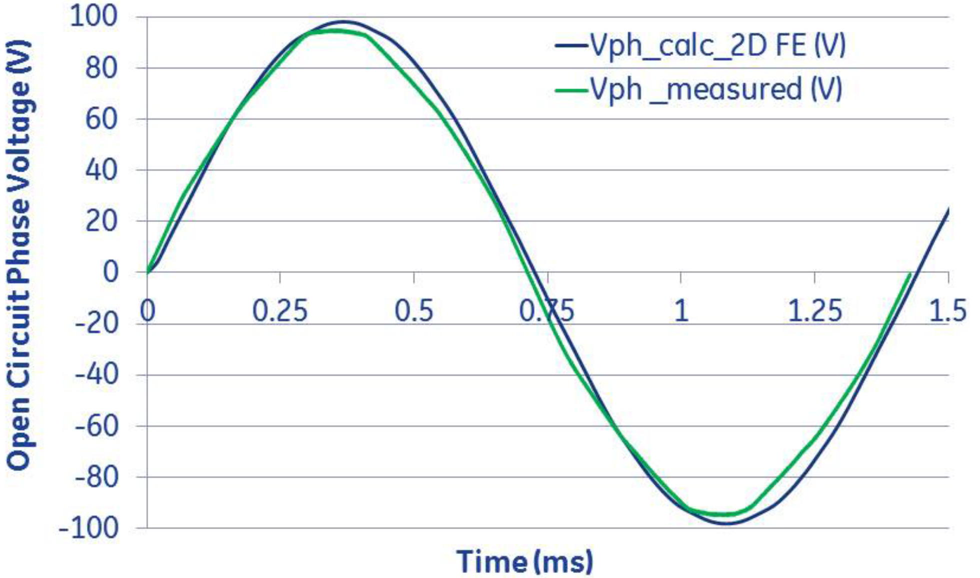
First GE prototype built using Dy-free magnets and tested under demanding test conditions in terms of demagnetization

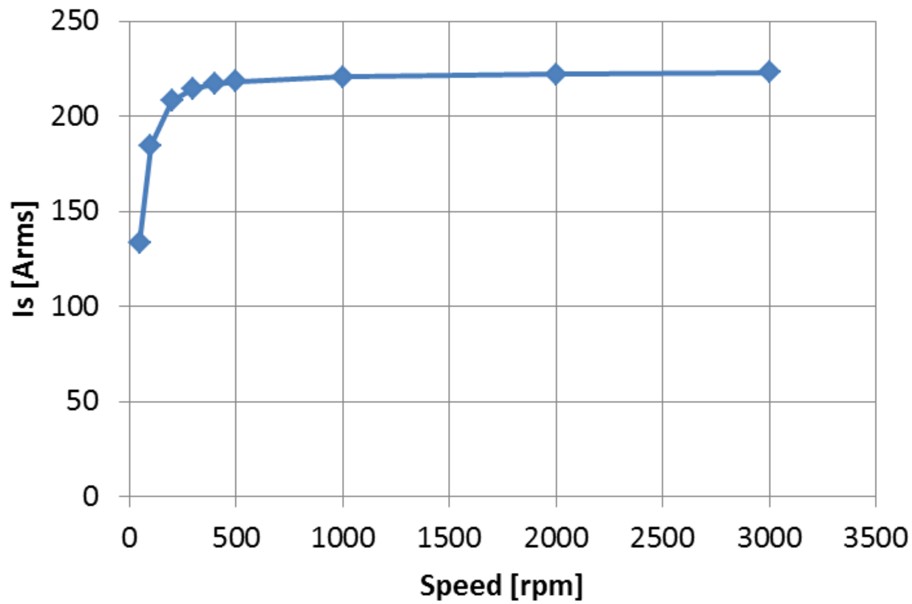
Tested Performance

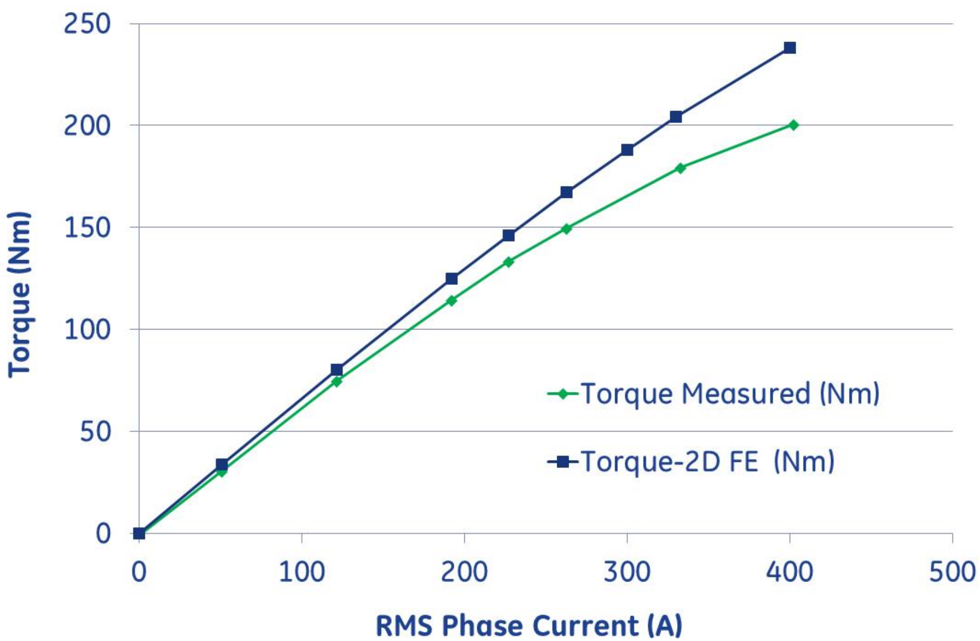
Speed [RPM]	Torque [Nm]	Pmec [kW]	Pelec [kW]	Eff [%]	Vph [Vrms]	Vll [Vrms]	Iph [Arms]	PF	Loss [kW]
2800	192.89	**56.54**	61.46	**91.99**	100.80	174.59	373.10	0.545	4.92
2800	125.34	**36.72**	38.90	**94.40**	77.81	134.77	217.10	0.768	2.18
4000	86.88	**36.37**	38.61	**94.20**	99.25	171.91	149.50	0.867	2.24
5000	62.08	**32.49**	35.35	**91.91**	110.89	192.07	109.60	0.970	2.86
6000	57.90	**36.38**	39.49	**92.12**	145.30	251.67	100.80	0.899	3.11
7000	51.10	**37.49**	40.84	**91.80**	140.90	244.05	98.00	0.986	3.35
8000	42.70	**35.79**	39.51	**90.60**	130.80	226.55	112.30	0.897	3.72
9000	44.60	**42.02**	46.07	**91.20**	134.50	232.96	128.60	0.888	4.05
10000	44.00	**46.12**	50.70	**91.00**	131.48	227.7	144.96	0.887	4.58

The prototype was capable of providing more than the required power within the voltage and current limitations and with good efficiencies

Test Results

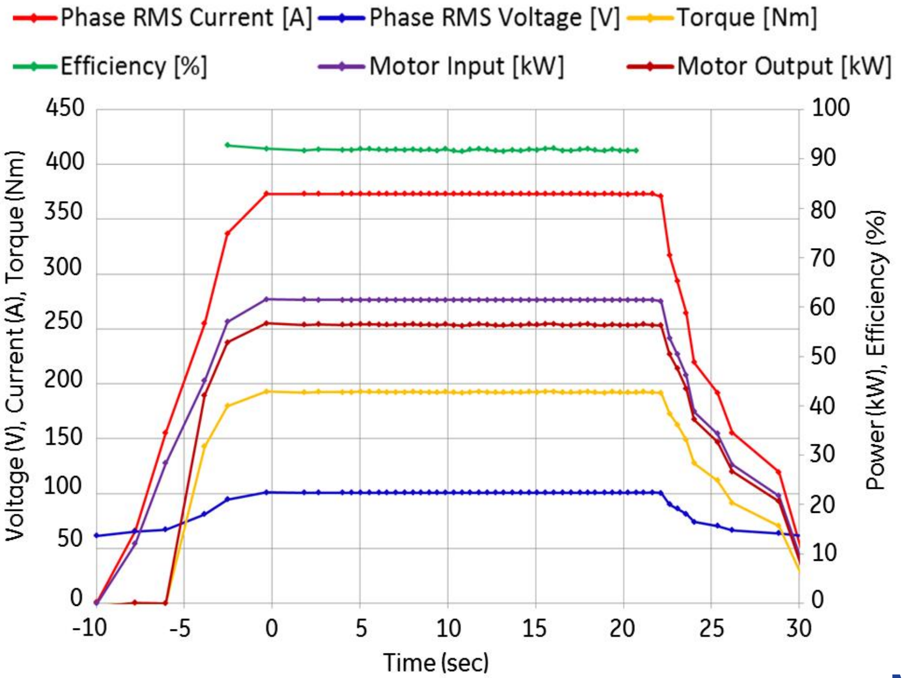




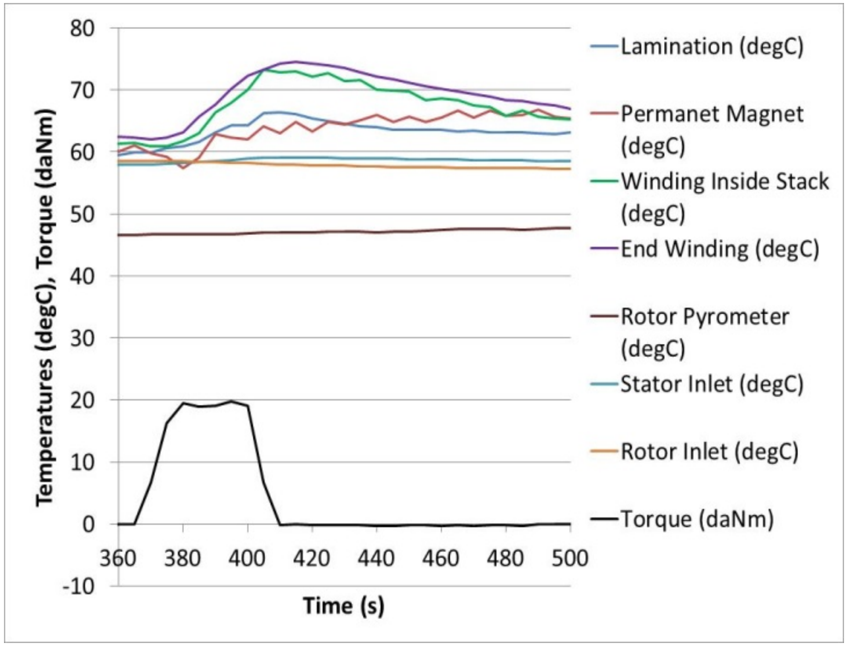


- Short circuit current very close to machine rated current (excellent flux-weakening and fault-tolerance capabilities)
- **No signs of demagnetization**
- Discrepancy in torque attributed to 3D effects which were already accounted for
- Machine able to provide 200Nm at 400 Arms (required 187.6Nm)

Peak Power



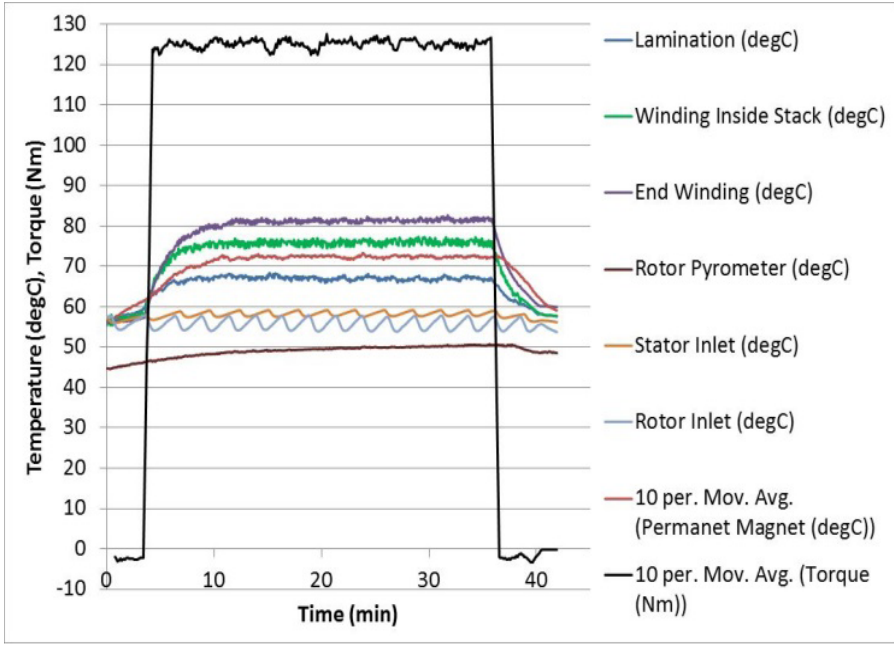
Measured Performance During 18 seconds Peak Power Operation



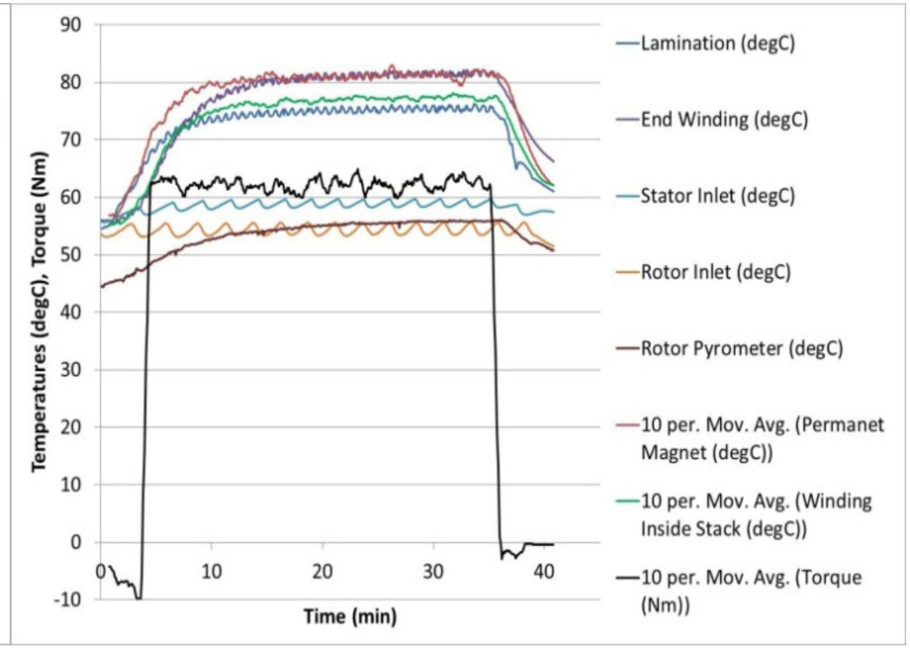
Measured Temperatures during a Heat Run for 18 seconds under 56.5 kW – 2800 rpm Peak Power Operation

- No signs of demagnetization
- Hot spot is in the end winding with a modest temperature rise of 16^{o}C (**effective cooling**)

Heat Runs at Rated Power



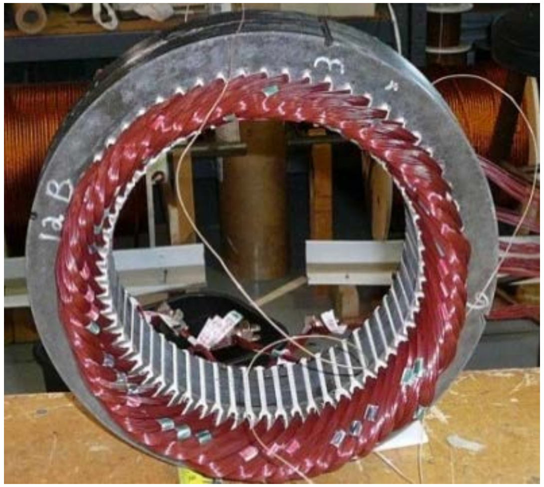
Measured Temperatures during a Heat Run under 36.7kW-2800rpm Continuous Operation

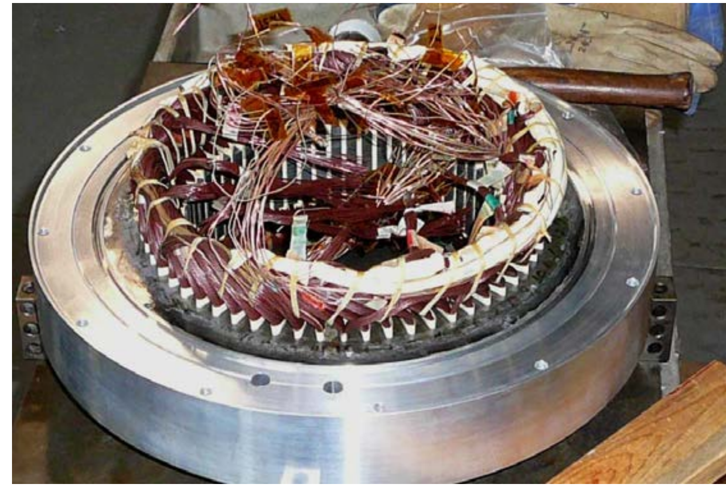


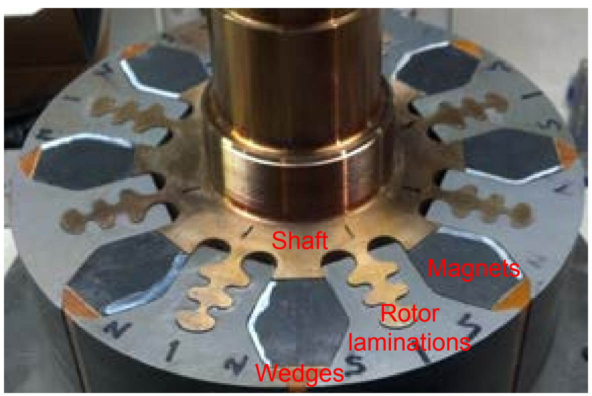
Measured Temperatures during a Heat Run under 32.3kW- 5000rpm Continuous Operation

- Machine is capable of producing more than the required 30 kW continuous power
- Modest temperature rises of 25^{o}C (**effective cooling**)

(2) Spoke-Ferrite Motor Prototype

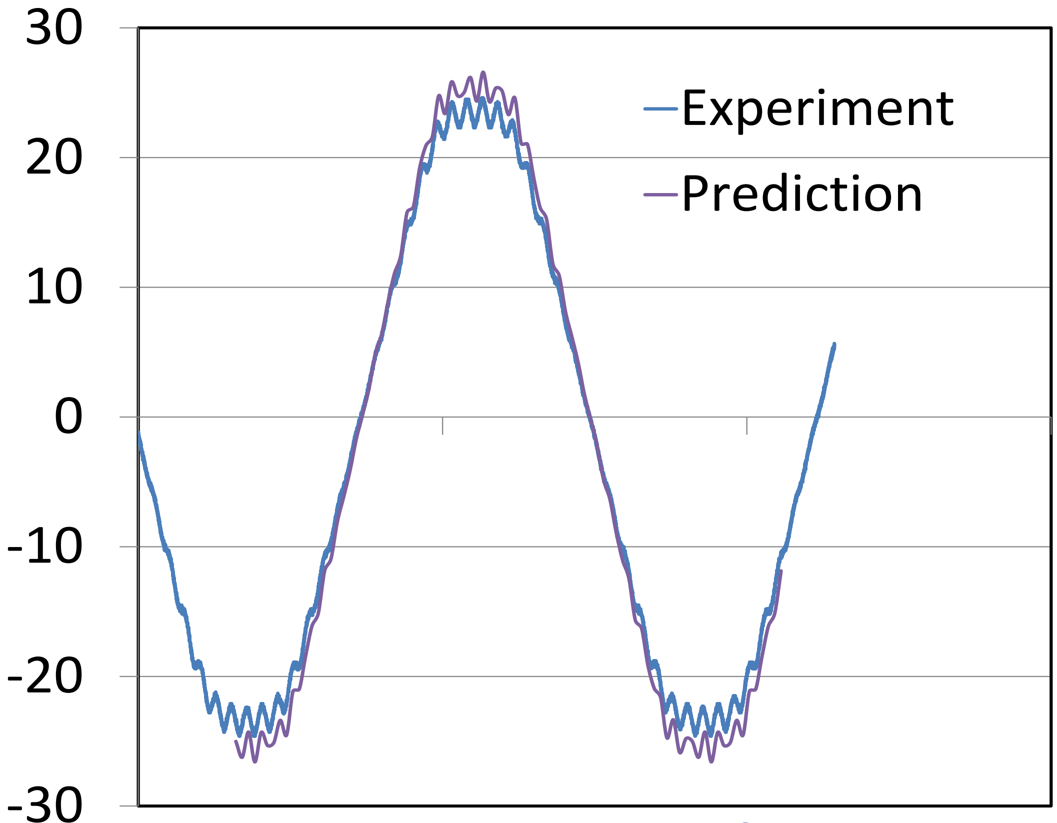






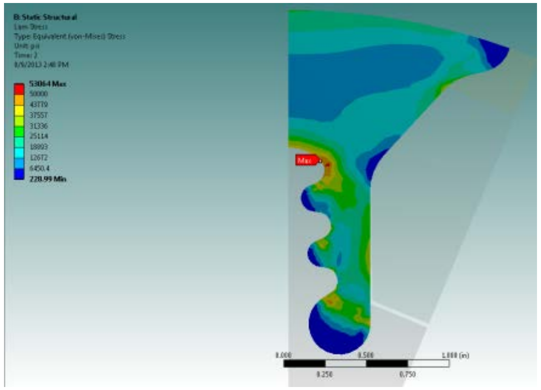
- ***Issues of torque ripple and ferrites demagnetization at low temperatures addressed***
- ***Several designs with different magnet grades analyzed***

Back-emf and Resistance Comparisons



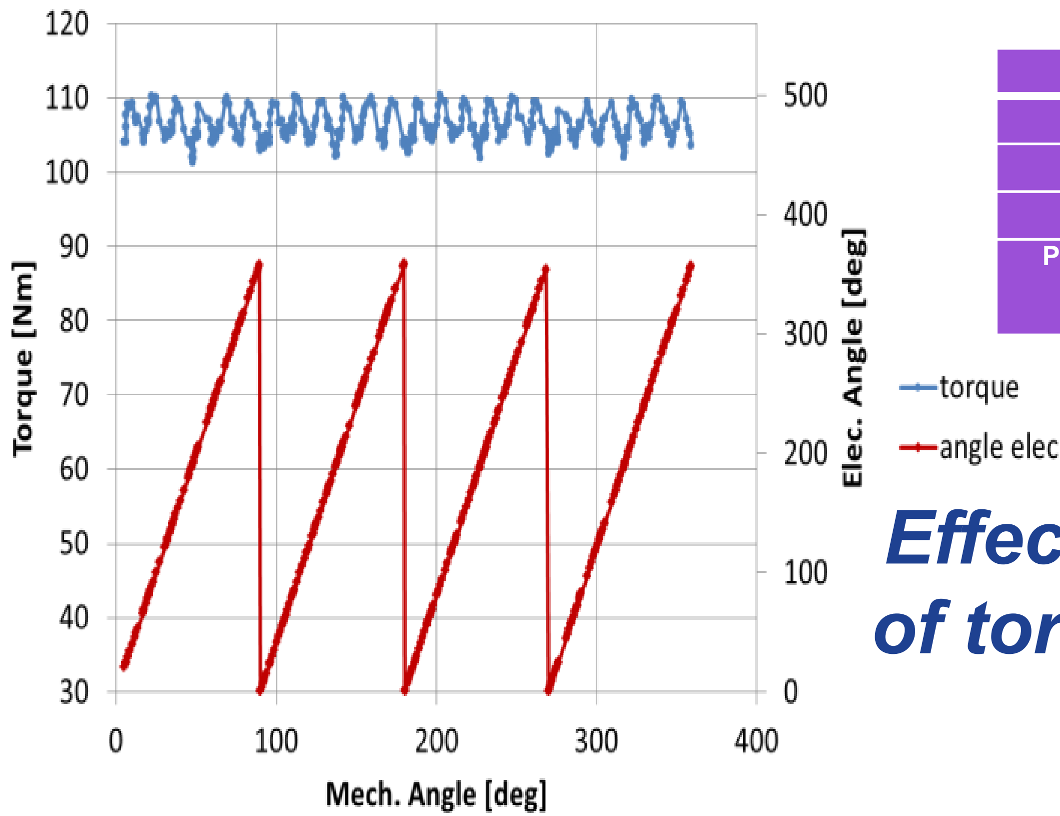
Experimental back-emf overlaid against predictions at a speed of 2000 rpm and room temperature

- ✓ Inexpensive Ferrite Magnets
- ✓ No need for rotor cooling
- ✓ Low AC losses
- ✓ Simpler control due to low frequency



Date	AC/DC	T [C]	RA1	RA2	RB1	RB2	RC1	RC2	RA	RB	RC	R(FEA)
14-Jan	DC	20							18.54	18.37	18.34	
27-Feb	AC	18.5							18.9	17.6	18.4	18.07
4-Mar	DC	20	42.4	42.5	42.5	42.6	42.3	42.3	21.225	21.275	21.15	18.07

Torque Ripple

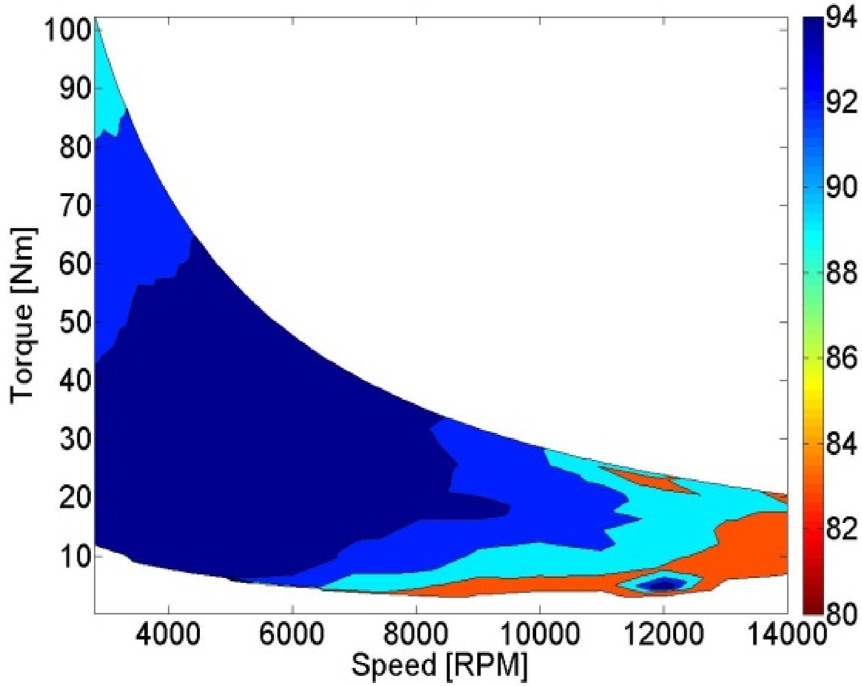


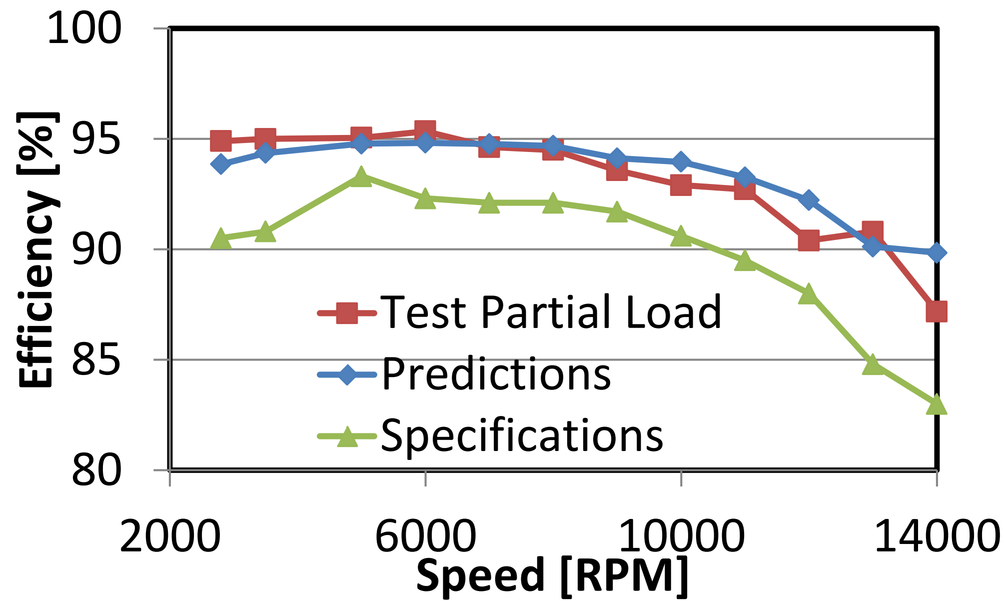
Condition	Pk-pk Ripple
Baseline Design	26.1%
Pole-shaping	16.8%
2.5 slot/pole/phase	9.4%
Pole-shaping + 2.5/ slot/pole/phase	6.0%

Effective implementation of torque ripple reduction techniques

Measured peak-peak torque ripple is 8.9 Nm at the rated torque

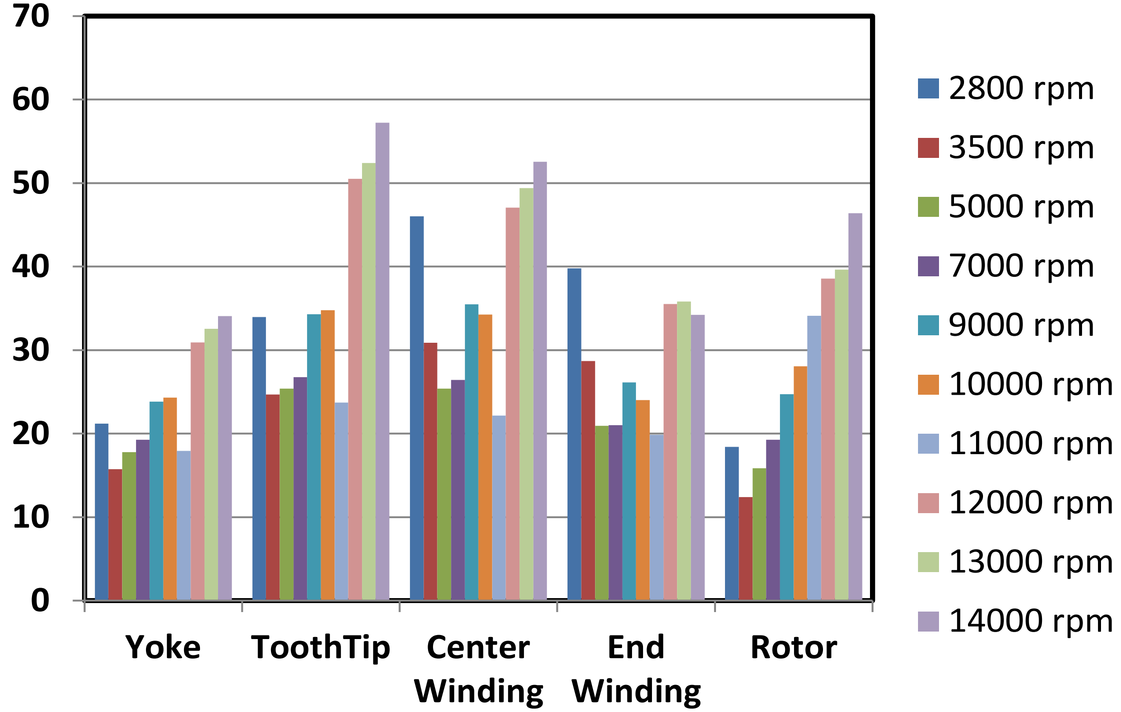
Efficiency Map





Significant advantages in terms of partial-load efficiency

Thermal Results



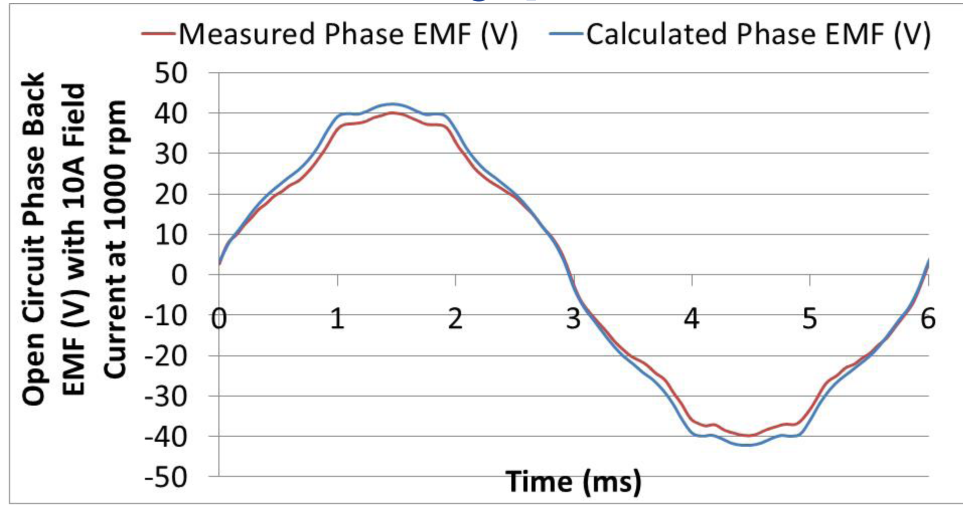
Measured Temperature Rise Inside The Machine as a Function of Speed Under Rated Power Testing

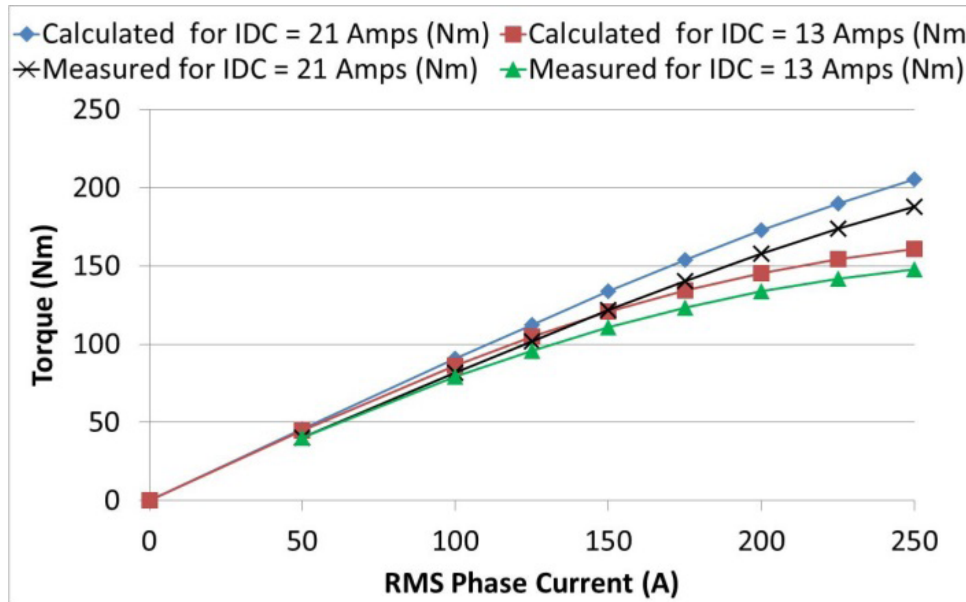
Effective cooling with no rotor cooling required

(3) DC-Biased SRM Prototype

Stator

Rotor





Good agreement between predictions and measurements

Partners/Collaborators

Logo	Organization	Role
	North Carolina State	Evaluation of motor topologies
	University of Akron	Evaluation of motor topologies
	University of Wisconsin	Evaluation of motor topologies
NREL NATIONAL RENEWABLE ENERGY LABORATORY	National Renewable Energy Lab	Evaluation of thermal management schemes
OAK RIDGE National Laboratory	Oak Ridge National Lab	Evaluation of motor topologies and materials
	Ames National Lab	High resolution microscopy of magnetic materials
	Arnold Magnetics	Specialized magnetic material processing and characterization

Remaining Challenges and Barriers

- Successful testing of the 4 motor prototypes in 2015 and confirming that their performance is close to predictions
- This will guide the down-selection of the final motor concept
- Developing the advanced materials with the required properties
- Being able to scale the materials up in time for the final motor build and test

Proposed Future Work

FY15

- Finish test proof-of-principle motors/materials
- Final selection of motor topologies/materials based on test results of proof-of-principle motors
- In FY2015, the processing of one or more non-rare-earth motor component materials will be scaled to level needed for insertion into a final machine prototype.
- Initiate design for final motor(s)

FY16

- Build and test final motor(s)

Summary

- Significant progress made since last year
- More than 10 motor topologies fully evaluated
- 9 filed patent applications with several others pending
- First motor prototype using Dy-free magnets built and fully tested
- Second motor prototype using ferrite magnets built and fully tested
- 2 topologies with no magnets are built and currently being tested
- Developed and scaled-up processing of high temperature (>250 °C) slot-liner insulation.
- Developed method for locally patterning non-magnetic regions on motor lams with < 100 μm interface widths that are stable > 5000 hours at 180 °C
- Produced test laminate with locally non-magnetic regions in preparation for scale-up.

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